Remote sensing of the environment

D. B. Morris and P. H. A. Martin-Kaye

The ever increasing demands on the Earth's natural resources and our corresponding concern with the preservation of the environment has encouraged the development of more sophisticated methods for the aerial survey of the Earth's surface than conventional photography hitherto widely used. The authors examine in detail two of these new remote sensing techniques—infra-red surveying and radar mapping—and describe some of the practical results so far achieved.

In a recent article in this journal (31, 130, 1972) B. H. Grimes and J. Hubbard described the many developments and applications of modern aerial photography and briefly mentioned the possibility of using other parts of the electromagnetic spectrum for the observation of the Earth's surface features. There are many reasons for this interest but a particular stimulus has been given to Earth surface studies by two more recent developments, namely side-looking radar (SLR) which can be used round the clock and in all weathers, and by infra-red scanners which enable the thermal properties of the Earth's surface to be measured. The new techniques are complementary to conventional aerial photography and multi-spectral photography and for each new application one must assess the relative merits of each technique with particular regard to effectiveness, resolution, all-weather capability, data processing and interpretation, availability, and cost.

Remote sensing may be defined as the detection from a distance of variations in the physical and chemical properties of the Earth's surface. There are several favourable 'windows' in the Earth's atmosphere that allow the detection of electromagnetic radiations from balloons, aircraft, rockets, and satellites, but the thermal infra-red and radar wavelengths demand particular attention. In both cases theory and practice have developed sufficiently to enable aircraft to undertake surveys on a world-wide commercial basis for a variety of purposes. Much of the early work was done under military auspices and it is only since 1968 that these systems have been available for civil applications.

The importance of remote sensing techniques has been recognized by the Committee on Science and Astronautics of the United States House of Representatives which in 1972 selected 'Remote Sensing of Earth Resources' as the subject for detailed appraisal. The techniques of remote sensing are being applied to a wide range of problems in agriculture, mineral exploration, pollution, and many other aspects of our environment, and received additional impetus from the launching by NASA of the Earth Resources Technology Satellite in July 1972.

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In Europe the European Space Research Organization (ESRO) has placed contracts for the study of many aspects of remote sensing including multi-spectral scanning, satellite radar systems, and data pre-processing.

The electromagnetic spectrum

In principle, any part of the electromagnetic spectrum (figure 1) may be used for remote sensing, ranging from short radio waves to visible light. In practice, it is necessary to select those wavelengths for which adequate detectors exist and for which the atmosphere is transparent. For these reasons the regions of most interest are the visible range (0·3–0·7 μm), the infra-red (0·7–14 μm) and the microwave range between 0·3 and 30 cm.

In a passive sensing system the radiation detected may have originated either at the Earth's surface or it may be radiation from the Sun that has been reflected by the Earth. Survey cameras and infra-red line scanning systems are passive systems.

In an active sensing system the radiation originates from a source carried by the aircraft and is then reflected back from the Earth to the detector. Side-looking radar is the most important active system, but lasers in the visible and infra-red bands are now being developed.

Planck's radiation law expresses the relationship between temperature and radiation for a perfect black body, the maximum radiant power emitted by both land and ocean surfaces being known to occur at infra-red wavelengths of about 10 μm. Wien's displacement law is a more convenient expression, expressing the wavelength of maximum emissive power for a black body as: $\lambda_{max} = 0{\cdot}8298/T$ where λ_{max} is measured in cm, and T is the absolute temperature.

At wavelengths of about 1 μm the radiation from the Earth's surface is predominantly reflected solar radiation and therefore attention has been concentrated on the two atmospheric 'windows' in the wavelength ranges of, between 3 and 5 μm and between 8 and 12 μm. In the first range the energy emitted by a perfect radiator increases approximately as the tenth power of the temperature thus giving very sensitive measurements of temperature difference. As there is still a considerable component of reflected radiation from the Sun at these wavelengths the second window is of greater interest because of the energy peak from the Earth's surface, even though the energy changes only approximately linearly with temperature.

Between 5 and 8 μm water vapour and carbon dioxide are strongly absorbing and this part of the infra-red cannot be used for remote sensing.

The detection of infra-red radiation

The infra-red detectors of widest application in aerial surveying utilize as thermosensitive transducers indium

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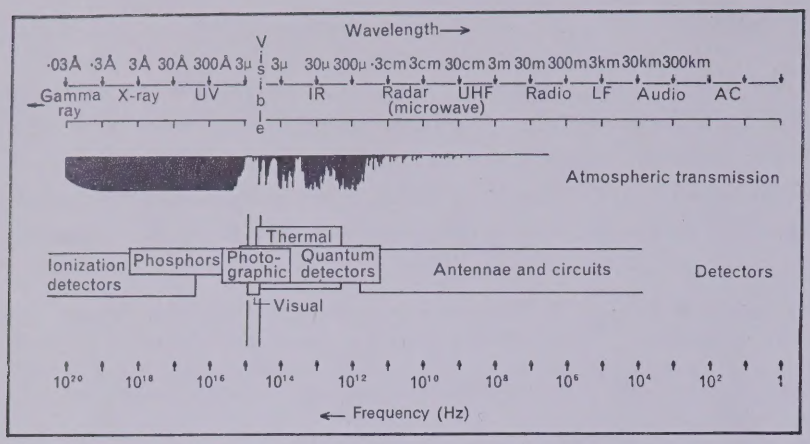

Figure 1 The electromagnetic spectrum.

antimonide in the 3–5 μm band and mercury cadmium telluride in the 8–12 μm band. The detectors are cooled to 77°K to permit them to operate at maximum sensitivity. The electrical output from the detector may be recorded on magnetic tape or used to produce a 70 mm black and white film record. Magnetic tape recording has the advantage of maintaining the full dynamic range of the signals from the observed scene and of allowing computer corrections and sophisticated processing such as density slicing. Recording directly on to film imposes limits on the sensitivity and dynamic range.

To obtain aerial coverage a mirror in the aircraft is rotated very rapidly and is arranged to scan at right angles to the path of the aircraft, the forward movement of which enables complete coverage to be obtained.

Infra-red imagery is distorted by roll and yaw of the aircraft and by variations in speed and height. In addition there is always a lateral distortion because the field of view is constant (2 milliradians), but the distance of the scanner from an object varies along the scanned line. For this reason the area of interest is generally confined to the central part of the imagery, that is a field of view of 70°. Modern scanners are therefore roll-stabilized and full correction of the imagery is obtained by computer processing.

For quantitative work an internal black body calibration source is necessary; in addition a Barnes PRT 5 radiation thermometer is used to measure the ground temperature.

Generally, airborne measurements of temperature agree well with those made on the ground. Differences occur because the airborne measurements are obtained from a larger surface area and depend on the thermal properties of a very thin surface layer whereas the ground measurement probably refers to a small area below the surface.

One disadvantage of infra-red imagery is that it is unsuitable for stereoscopic examination as the principles of perspective geometry do not apply. However, the high spatial resolution of infra-red scanners (typically 0·5 m from a height of 300 m) can assist in the correlation of infra-red imagery with ground features.

Applications of infra-red surveys

Because infra-red surveys are used to measure surface temperatures a great deal of care must be taken to select the most appropriate time for the survey. Generally infra-red surveys are flown at night when differential solar heating and shadow effects are minimal. For some applications it may be found that daytime flying is the most effective but the imagery is then generally dominated by topographic effects caused by differential solar heating.

For night flying, safety and navigation become very

Figure 2 Infra-red thermal image of River Exe showing warm water over shallow sand banks being moved by the tide. The white specks are small boats.

important considerations. Modern survey aircraft are equipped with Doppler navigation or with radio-navigational systems such as Decca and Raydist, enabling their position to be known within one or two hundred metres. Surveys are not flown when the ground is covered with mist or fog and as a rule it is advisable not to fly immediately after heavy rain, which can eliminate the thermal contrasts of interest.

The season of the year also affects the thermal contrast, thus, for example, it is best to fly in the spring to detect fresh-water seepages off the south coast of England. The Water Resources Board have now flown three surveys around the coast of England to locate offshore fresh water seepages, and great care is necessary in selecting the most appropriate conditions of tide and wind to obtain the best results. Figure 2 illustrates a recent survey made off Devon.

As part of the United Nations geothermal survey in the Rift Valley of Ethiopia an airborne infrared survey was made to locate all surface temperature anomalies that were 5°C above background and had a diameter exceeding 6 m. In the inaccessible area of the Danakil depression it was possible to cover an area of 40 000 km² in just one month of flying. The crew of the authors' firm flew every sortie between midnight and 06.00 h to avoid solar heating effects, and a flying height of 3000 m was both safe (over the volcanoes) and adequate with the sensor resolution of 2 milliradians. The flight line spacing of 5 km ensured complete coverage of the survey area and by processing the film on site the UN field parties were able to check the results within 24 hours of each survey. As a result of the survey, over 500 new surface thermal features were identified and the structural control of the geothermal areas is now much better known.

Radar mapping

Radar has now been used for some considerable time in surveillance and monitoring. Current marine and air traffic densities would be virtually impossible without this means of watching changing events beyond eyesight range and through fog, cloud, haze, and darkness. Cloud-covered parts of the world can equally well use this all-weather capability and independence of daylight conditions in meeting basic mapwork needs. The authorities in many such areas are now turning to radar imaging of the terrain as a rapid and effective alternative to air photography.

The results obtainable from sophisticated radar mapping systems are impressive. As figures 3 and 4 show, an image similar to a conventional aerial photograph of the ground is obtainable and can be recovered with the same facility by night as by day and regardless of cloud cover. The examples illustrated were all obtained from an aircraft flying at 400 km/h at 6000 m and above cloud cover, often complete and of as many as three layers.

The value of this mapping technique for regions ordinarily beset by cloud is evident. Air photographic survey companies, even for favourable regions, avoid fixed-price contracts since they are only too well aware that few guarantees can be given on the time that will be necessary to obtain results of good quality. It is, in fact, not unusual for programmes to be persistently

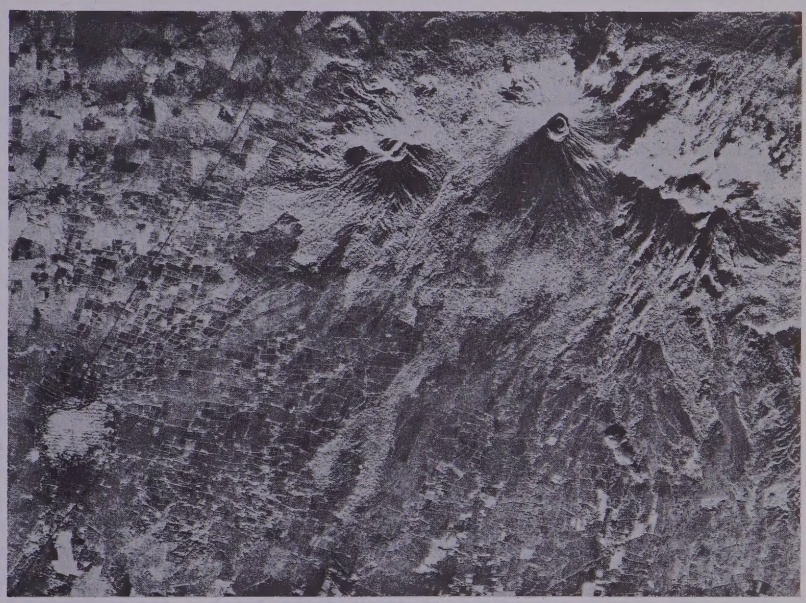

Figure 3 SLR image of the Chinandega Town and San Cristobal volcano area of Western Nicaragua. The volcanic forms, urban area, woodlands, cultivation pattern and highways are clearly visible. The N-S distance across the imaged area is about 20 km.

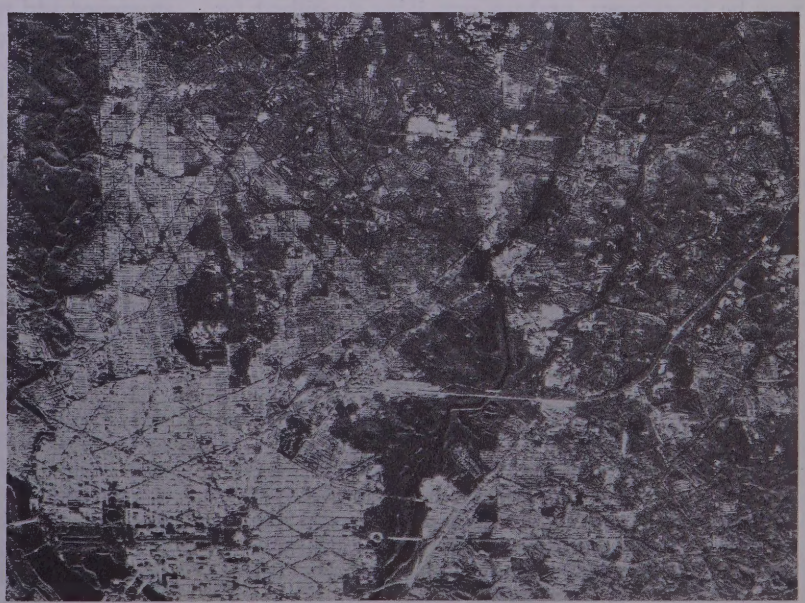

Figure 4 SLR image of part of Washington, D.C.

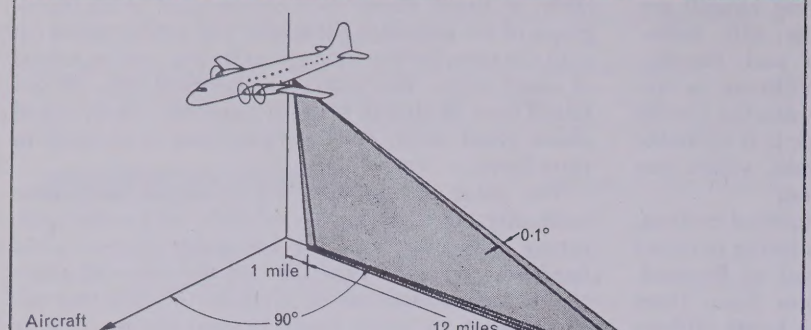

Figure 5 The geometry of side-looking radar.

frustrated, sometimes over successive seasons, and occasionally to be abandoned entirely. When concluded, the results are apt to be of very variable quality, often with disagreeable cloud content. Tones then reflect a variety of light conditions, and the data represent a mixture of seasonal variations.

Radar mapping is free from these problems: surveys can rapidly proceed to a fixed timetable and price, enabling dependent projects and teams to be scheduled and mobilized in accord. This can provide a tremendous stimulus for planning and operations, and in the optimum use of manpower.

About 18 million square kilometres of the Earth's surface—mainly underdeveloped areas of the equatorial regions—are rated as particularly difficult for air photography. For these areas, radar mapping offers a speedy means of providing serviceable maps and an inventory of basic resources, lack of which is a severe impediment to effective regional planning and development.

Whenever good photography is possible the total information content is greater than with side-looking radar since better resolution can be obtained. On the other hand, for regional purposes, much of this information may be superfluous, perhaps remaining unutilized for years, whilst with pressing problems delays cannot be tolerated.

Mapping radars use fixed antennae directing the beam laterally from the aircraft (figure 5). The mode of display of a conventional scanning radar is generally familiar. It depends upon the scan by a directional microwave beam transmitted from a rotating antenna, repetitively registering and updating reflected information upon a cathode-ray tube. Mounted on aircraft, radars of this type can give excellent impressions of the main features of the terrain below. The c.r.t. display information is transitory, but can be captured from the screen by photography. Were film to be tracked across the screen at a rate proportioned to ground speed a strip image of a continuous swath could be produced. Such an arrangement would however yield very crude results and can readily be improved upon. Once stationary ground objects have been recorded there is no need for them to be viewed again, nor for the repeated sweep of a rotating antenna. A lateral beam from the aircraft will suffice as its forward motion will bring new ground into the inspection range. This is the basis of radar mapping.

Fixed antennae have the gre advantage that they can be larger, an thus have better performance, tha any rotating system mountable o aircraft. Moreover the sweep-typ c.r.t. can be replaced by one of linea display and greater finesse. Sinc radar map compilation is progressive the new information of each puls adding fractionally to the construc tion of the strip image, high-qualit linear-display cathode-ray tubes ca register much detail.

Commercial imaging is usuall performed with 'acquisition' scale of 1 : 200 000 to 1 : 400 000, takin in swath widths of 20–40 km. Enlarge ment is satisfactory to a scale of abou 1 : 50 000 after which no interpreta tional advantage is obtained. Although inspection o the terrain is from the side, bias can be given to th c.r.t. to yield a print-out corrected to ground range giving the impression of vertical view. Correc correlation of the forward speed and film tracking to the radar's lateral ranging yield consistent scales in any direction under 'flat earth' conditions. Adjacent imagery strips can be easily joined to form impressive mosaics presenting synoptic views of large areas.

The Earth's surface is not, however, flat and certain distortions occur which become noticeable in mountainous terrain. This can be readily understood from the following example, when we moreover bear in mind that radar is a distance-ranging device. Return reflections arrive sooner from nearer objects than those farther away. The top of a high building will be nearer the aircraft than the base and, hence, is recorded first. The effect is that the face of such a building would appear to overlie its immediate foreground rather than the background as is the case in oblique air photography. Few buildings are large enough to make this effect of consequence but the characteristic is apparent in mountainous country in which facing slopes are foreshortened and reverse slopes correspondingly elongated. The effect lessens with decreasing angles of inspection, that is at greater distances from the aircraft. On the other hand, distance imaging introduces increasing shadow in hilly country. Intermediate imaging distances are generally used for mosaicing, combining acceptable level of relief distortion without introducing excessive shadow.

Resolution obtainable in radar depends however upon completely different considerations from those of photography and, rather oddly, does not depend upon proximity. If two separately detectable objects, for example, two radar reflectors, are placed close together below resolution level, radar will register them in a single echo from far beyond eyesight range. Approach would eventually distinguish them to the eye, but still not separate them in the radar response, the discriminatory capacity of which is not optical but depends upon the duration of each radar pulse, which remains constant irrespective of distance, and upon the directional sharpness of the beam. Current commercial systems offer a resolution of about 10 metres. The expected lifting of secrecy on certain existing military equipment may well

bring improvement to about 3 m and this, presumably, will again be bettered.

Various wavebands are utilized. Most surveying has been carried out with K_a-band and X-band radars (1–3 cm). An interesting possibility, yet to be commercially offered, is the use of multiband systems. Depth of penetration increases with wavelength. Ascription of suitable colour to the various reflected wavelengths, and combination into a single image may promise radar something of the equivalence of colour to the black and white photograph. This offers the prospect of an important addition to interpretational dimension. Again, since radar emissions may be plane-polarized, target changes of the polarization have already been shown to give interpretationally significant information. Generally, however, there has not yet been much demand for such sophistication in commercial work.

Normal photography, recording in visible wavelengths, registers different characteristics from those of radar. Variations in tone on a photograph depend upon brightness and colour; in radar they depend upon granularity, dielectric constant, and attitude of the inspected face to the impinging beam. Despite these differences the radar image and the photograph are remarkably similar in many respects. The illustrations (figures 3 and 4) show many features familiar to the photo-interpreter.

The system outlined at the beginning of this section is essentially that of 'real aperture' instrumentation in which the physical dimensions of the antenna produce sharp directionality of the beam. This is a serviceable arrangement, capable of excellent performance in nearer distances. 'Synthetic aperture' systems utilize the aircraft's forward progress to simulate antennae of yet greater lengths. Doppler effects in the returns enable information to be extracted from a narrow portion of the beam, which in this case fans much more broadly.

It is not necessary to record the data immediately on film; they can be stored on tape for later recovery either in photographic or digitized form. A monitoring radar on a satellite would be likely to obtain a great deal of superfluous information. For many purposes instrumental data processing, identifying where change had occurred, would save much visual search and comparison of observations repeated over the same area.

The potential value of radar mapping is by no means restricted to bad-weather areas. The speed and reliability of imaging enables the system to be applied to many monitoring objectives some of high operational utility. Amongst these are the mapping of the state of the sea and its ice, monitoring of sea traffic, snow distribution, reservoir conditions, extent of floods, changes of navigable channels, positioning of navigational aids, tracking oil slicks at sea and location of leaks in submarine pipelines. These are matters with operational objectives which can lead to prompt decision, economy and efficiency. ESRO is at present investigating the feasibility of mounting a side-looking radar on a satellite. Such a system could solve many problems that need early, reliable information on changing circumstances, and that are otherwise difficult to monitor.

High-resolution radar mapping clearly requires elaborate equipment. The radar units themselves are highly sophisticated; the antennae must be gyro-stabilized; and the registering systems have to be linked with doppler and inertial navigation systems. Heavy aircraft capable of high altitude flying are required, operated by experienced crew and technicians. Radar mapping thus finds its best economic justifications for large-area surveys or for crucial problems requiring immediate answers. Radar would appear to be the ideal system for mapping other planets in the solar system but meanwhile will find many applications on Earth.

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Lithium, manic-depression, and the chemistry of the brain

David Samuel and Zehava Gottesfeld

The therapeutic properties of lithium as a constituent of mineral waters have been of benefit to man since Roman times, but it is only in the past two decades that the salts of this chemically most singular element have been used in the effective treatment of mental disorders. Although lithium therapy has been extensively investigated, its mechanism is still far from perfectly understood. This article surveys experimental work on the biochemistry of lithium in the brains of both animal and human subjects and gives a critical appraisal of current theories of its action.

Lithium is the lightest of the alkali metals and exhibits somewhat anomalous physicochemical properties due to the unexpectedly large difference in electronegativity between it and the succeeding elements in Group IA of the Periodic System. This anomaly is manifest both in the properties and in the reactivity of the element itself, a silvery-white metal discovered in Berzelius' laboratory in 1818. What is of particular interest to chemists are the strikingly anomalous properties of lithium compounds [1]. These include the following:

1. Lithium salts of large polarizable anions are markedly less stable than those of sodium and potassium—the bicarbonate, superoxide, and hydrosulphide for instance, are too unstable even to exist at room temperature.
2. Compounds containing lithium are more covalent in character than those of the other alkali metals; thus the halides are more soluble in organic solvents and can be separated in this way. In addition, complexes formed with either oxygen or nitrogen donor ligands are more stable than those of sodium or potassium.
3. Lithium salts of anions with high charge densities such as the hydroxide, carbonate, phosphate, and fluoride are less soluble in water than those of other alkali metals.
4. The so-called 'diagonal relationship' in the Periodic Table is particularly marked in the case of lithium whose salts resemble those of magnesium and to some extent even calcium of Group IIA.

Lithium, as its name indicates, is found in many rocks and minerals and is slowly leached out by ground-water. The natural lithium content (1 meq or 7 mg per litre) of certain 'mineral springs' in Europe may underlie their therapeutic properties and the supposed benefits of 'taking the waters', a practice dating from Roman times. In the latter half of the nineteenth century lithium became a recognized treatment for physical diseases caused by the deposition of uric acid in different parts of the body. It was found that pains due to kidney stones, gravel, gout, and rheumatism were alleviated, probably because of the increased solubility of lithium urate. For less obvious reasons, lithium was also recommended for various nervous diseases, including neuralgia, depression, 'nervous breakdown' and even epilepsy. However, none of the claims for the efficacy of lithium were ever effectively investigated or substantiated.

Lithium salts have also been used in other minor ways. The bromide was used as a sedative for some time and during the late 1940s lithium chloride became a popular salt substitute in the United States for patients on sodium-free diets. However, after at least four deaths [2] and a number of serious non-fatal poisonings due to its unexpected effects on patients with [illegible] kidney [illegible]anned

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